

Reviewing the Evidence for Pentaquarks

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Abstract. Several experimental groups have reported evidence for baryons with flavor exotic quantum numbers that cannot be explained as qqq bound states but require a minimum of five quarks – $qqqq\bar{q}$. These pentaquark states include the θ^+ , the Ξ^{--} and the θ_c . The reported widths of these new states are consistent with experimental resolution and may be as narrow as a few MeV/c^2 or less. Prior to 2003, experimental searches for flavor exotic baryons spanning several decades yielded negative results. There have also been a number of searches carried out since the reports of these new pentaquark states that do not confirm their existence. This review of both the positive and negative reports seeks to understand the current situation regarding the experimental evidence for pentaquarks.

1. Introduction

It is noteworthy that except for one or two possible exceptions in the meson sector, the hundreds of known hadrons can be described as bound states of three quarks (qqq), in the case of baryons, or a quark and anti-quark ($q\bar{q}$), in the case of mesons. There have been reports of possible evidence of mesons with exotic J^{PC} quantum numbers, not possible for $q\bar{q}$, but until 2003, no reports of baryons with quantum numbers inconsistent with qqq . There were searches in the 1960's and 1970's for what was then referred to as the Z^* – a baryon with positive strangeness. The review by Hey and Kelly [1] discusses these early searches, mostly in bubble chamber experiments, and a more recent review by Trilling of the current exotic baryon sightings [2] lists publications reporting on bubble chamber experiments with incident π and K beams searching for the Z^* . Those experiments found no enhancements in $S = +1$ baryon channels. Indeed the failure to find such flavor exotic baryons in the 1960's and 1970's lent credence to the then nascent quark model.

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In 1997, D. Diakonov, V. Petrov and M. Polyakov [3], using a chiral soliton model, predicted a $J^P = \frac{1}{2}^+$ exotic anti-decuplet of pentaquark baryons (see Figure 1) including a $uudd\bar{s}$ baryon with positive strangeness, isospin zero and a mass of $1530 \text{ MeV}/c^2$ with a width of $15 \text{ MeV}/c^2$. Evidence for that state, the θ^+ , has been reported by several experiments. That anti-decuplet is also predicted to include a $\Xi_5^{--} = ddss\bar{u}$ and a $\Xi_5^0 = udss\bar{d}$ for which evidence has also been reported. Yet another experiment claims an anti-charm pentaquark baryon, $\theta_c = uudd\bar{c}$. These findings have generated much excitement in the nuclear and particle physics theory community – nearly 300 papers have been written on the interpretation of these states and their properties. But as will be discussed below, these purported discoveries have also inspired recent searches that fail to find evidence for these states.

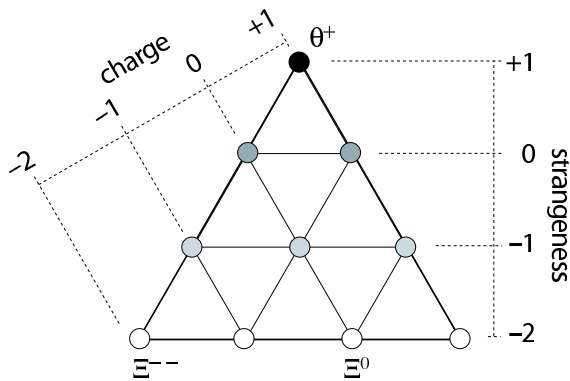


Figure 1. The predicted anti-decuplet [3] of pentaquark baryons indicating, in particular, the states $\theta^+ = uudd\bar{s}$, $\Xi_5^{--} = ddss\bar{u}$ and $\Xi_5^0 = udss\bar{d}$. Evidence for these states have been presented as well as for a $\theta_c = uudd\bar{c}$. Other searches for these states have yielded null results.

2. Experiments claiming positive pentaquark signals

Table 1 lists the experiments claiming evidence for pentaquark states. There are eleven experiments claiming a θ^+ , a state with $S = +1$, a mass of about $1.54 \text{ GeV}/c^2$ and a width consistent with being less than the mass resolutions of the the experiments. The state is observed through its decay into either K^+n or $K_S^0 p$. The first five reactions listed in Table 1 used a photon probe of relatively low energy, a few GeV, and the purported pentaquark is observed in the K^+n mode. The first sighting of the θ^+ was from the LEPS experiment at Spring8 [4, 5] followed shortly thereafter by the CLAS experiment at Jefferson Lab [6, 7]. The SAPHIR experiment is also a low-energy photon experiment [8].

The final state neutron in the above five experiments is not detected. In the LEPS experiment the assumed K^+n effective mass is actually the missing mass recoiling against the K^- . In the CLAS(d) experiment the assumption is that the final state proton, which is detected, is the spectator nucleon and the K^+n effective mass is the mass recoiling against the K^-p system. In the CLAS(p) experiment the neutron is inferred from missing mass and in the SAPHIR experiment the neutron is inferred from kinematic fitting.

The COSY experiment used a low-momentum proton beam [9] spanning the momentum range from 2.85 to 3.3 GeV/c. The JINR result comes from an analysis of collisions in a propane bubble chamber exposed to a 10 GeV/c proton beam. The SVD experiment [11] at IHEP studied pA collisions at 70 GeV/c. Both the DIANA and νBC groups re-analyzed old data from a liquid xenon bubble chamber (in the case of DIANA) [12] and the CERN BEBC and the FNAL 15-foot chamber (in the case of νBC) [13] – the former using a low-energy K^+ beam, the the latter neutrinos. The NOMAD experiment at CERN was built to search for neutrino oscillations [14]. The HERMES experiment at DESY found evidence for the θ^+ with quasi-real photons [15] and ZEUS claims evidence [16] for the θ^+ in ep collisions. The evidence for the the θ^+ presented in references [4, 5, 6, 7, 8] is in the K^+n mode, which is manifestly flavor-exotic while the other experiments report the θ^+ in the $K_S^0 p$ mode, which is a linear combination of $S = +1$ and

Table 1. Positive signals for pentaquark states. Please see the text regarding the final state neutron in the LEPS, CLAS and SAPHIR experiments.

Experiment	Reaction	State	Mode	Reference
LEPS(1)	$\gamma C_{12} \rightarrow K^+ K^- X$	θ^+	$K^+ n$	[4]
LEPS(2)	$\gamma d \rightarrow K^+ K^- X$	θ^+	$K^+ n$	[5]
CLAS(d)	$\gamma d \rightarrow K^+ K^- (n)p$	θ^+	$K^+ n$	[6]
CLAS(p)	$\gamma p \rightarrow K^+ K^- \pi^+ (n)$	θ^+	$K^+ n$	[7]
SAPHIR	$\gamma p \rightarrow K_S^0 K^+ (n)$	θ^+	$K^+ n$	[8]
COSY	$pp \rightarrow \Sigma^+ K_S^0 p$	θ^+	$K_S^0 p$	[9]
JINR	$p(C_3H_8) \rightarrow K_S^0 p X$	θ^+	$K_S^0 p$	[10]
SVD	$pA \rightarrow K_S^0 p X$	θ^+	$K_S^0 p$	[11]
DIANA	$K^+ Xe \rightarrow K_S^0 p (Xe)'$	θ^+	$K_S^0 p$	[12]
ν BC	$\nu A \rightarrow K_S^0 p X$	θ^+	$K_S^0 p$	[13]
NOMAD	$\nu A \rightarrow K_S^0 p X$	θ^+	$K_S^0 p$	[14]
HERMES	quasi-real photoproduction	θ^+	$K_S^0 p$	[15]
ZEUS	$ep \rightarrow K_S^0 p X$	θ^+	$K_S^0 p$	[16]
NA49	$pp \rightarrow \Xi \pi X$	Ξ_5	$\Xi \pi$	[17]
H1	$ep \rightarrow (D^* p) X$	θ_c	$D^* p$	[18]

$S = -1$. Several of these experiments studied the $K + p$ spectrum and found no evidence for a θ^{++} , thus concluding that $I = 1/2$ for the θ^+ .

At first glance, the evidence for the θ^+ seems convincing. The experiments claim signals with a statistical significance ranging from 4 to 7 standard deviations over background (we will return to this issue later). The evidence comes from low-energy and high energy experiments and experiments with a variety of beams: photons (real and quasi-real), electrons, protons, neutrinos and positively charged kaons.

Evidence for the pentaquark cascade states, Ξ_5^{--} and Ξ_5^0 , comes from a single experiment, NA49 at CERN [17], in the $\Xi^- \pi^-$ and $\Xi^- \pi^+$ modes in proton-proton collisions at $\sqrt{s} = 17.2$ GeV. The reported mass is $1.862 \text{ GeV}/c^2$ and the width is consistent with being below detector resolution. And evidence for the anti-charmed pentaquark, θ_c , also comes from a single experiment, H1 at HERA [18], in the $D^{*+} \bar{p}$ and $D^{*-} p$ modes at a mass of $3.1 \text{ GeV}/c^2$ and a width consistent with detector resolution. The data were collected in ep collisions at \sqrt{s} of 300 and 320 GeV.

3. Pentaquark searches with null results

Table 2 lists recent experiments that have searched for and failed to find evidence for pentaquark signals. As discussed earlier [1, 2], searches for $S = +1$ baryons in the 1960's and 1970's also failed to find evidence for their existence.

The experiments in Table 2 are listed in alphabetical order by name. For each of the three pentaquark states (θ^+ , Ξ_5 and θ_c), we indicate with a \uparrow that the state was observed or with a \downarrow that the state was searched for and not observed. The entry $(-)$ indicates that the state was not searched for.

Of the 18 entries in Table 2, 16 searches for the θ^+ yielded null results. One experiment, WA89 [36], that failed to find the Ξ_5 , did not search for the θ^+ and another experiment, ZEUS, that searched for and failed to find either the Ξ_5 or θ_c did claim positive evidence for the θ^+

[16, 37, 38]. All of the experiments (9 of them) searching for the Ξ_5 failed to find the state and all of the experiments (6 of them) searching for the θ_c failed to find that state. As will be discussed below, the experiments listed in Table 2 are characterized by high statistics and excellent mass resolution, of order 1 to 2 MeV/ c^2 in most cases. These experiments also see the relevant *benchmark* states, such as the $\phi(1020)$, $K^*(890)$, D^* , $\Lambda(1520)$, $\Xi(1320)$ or $\Xi(1530)$, with statistics that overwhelm experiments that report positive pentaquark sightings.

Table 2. Recent negative searches for pentaquark states. For each pentaquark state (P) we indicated with a $-$ that the state was not included in the search while \Downarrow indicates that the state was searched for and not observed and \Uparrow indicates that the state was searched for and observed.

Experiment	Search Reaction	θ^+	Ξ_5	θ_c	Reference
ALEPH	Hadronic Z decays	\Downarrow	\Downarrow	\Downarrow	[19]
BaBar	$e^+e^- \rightarrow \Upsilon(4S)$	\Downarrow	\Downarrow	$-$	[20]
BELLE	$KN \rightarrow PX$	\Downarrow	$-$	\Downarrow	[21]
BES	$e^+e^- \rightarrow J/\psi(\psi(2S)) \rightarrow \theta\bar{\theta}$	\Downarrow	$-$	\Downarrow	[22]
CDF	$p\bar{p} \rightarrow PX$	\Downarrow	\Downarrow	\Downarrow	[23]
COMPASS	$\mu^+(\text{}^6\text{Li}D) \rightarrow PX$	\Downarrow	\Downarrow	$-$	[24]
DELPHI	Hadronic Z decays	\Downarrow	$-$	$-$	[25]
E690	$pp \rightarrow PX$	\Downarrow	\Downarrow	$-$	[26]
FOCUS	$\gamma p \rightarrow PX$	\Downarrow	\Downarrow	\Downarrow	[27]
HERA-B	$pA \rightarrow PX$	\Downarrow	\Downarrow	$-$	[28]
HyperCP	$(\pi^+, K^+, p)Cu \rightarrow PX$	\Downarrow	$-$	$-$	[29]
LASS	$K^+p \rightarrow K^+n\pi^+$	\Downarrow	$-$	$-$	[30]
L3	$\gamma\gamma \rightarrow \theta\bar{\theta}$	\Downarrow	$-$	$-$	[25, 31]
PHENIX	$AuAu \rightarrow PX$	\Downarrow	$-$	$-$	[32]
SELEX	$(\pi, p, \Sigma)p \rightarrow PX$	\Downarrow	$-$	$-$	[33]
SPHINX	$pC(N) \rightarrow \theta^+C(N)$	\Downarrow	$-$	$-$	[34]
WA89	$\Sigma^-N \rightarrow PX$	$-$	\Downarrow	$-$	[36]
ZEUS	$ep \rightarrow PX$	\Uparrow	\Downarrow	\Downarrow	[16, 37, 38]

The ALEPH, DELPHI and L3 experiments ran at LEP. The ALEPH [19] and DELPHI [25] searches studied hadronic Z decays while L3 [25, 31] searched for the θ^+ in photon-photon collisions. The BaBar, BELLE and BES experiments are also all carried out at e^+e^- colliders. BaBar searched [20] in final states from $e^+e^- \rightarrow \Upsilon(4S)$ as well as 40 MeV below resonance while BES [22] searched in $e^+e^- \rightarrow J/\psi(\psi(2S)) \rightarrow \theta\bar{\theta}$. And BELLE searched for θ^+ in kaon interactions in the detector material [21] – a search that yielded 16000 $\Lambda(1520) \rightarrow pK^-$ decays but no θ^+ signal. The CDF experiment at FNAL searched for all three pentaquark states [23] in $p\bar{p}$ collisions. The E690 [26], FOCUS [27], HyperCP [29] and SELEX [33] searches were all carried out in fixed target experiments at FNAL. FOCUS used a photon beam produced by bremsstrahlung of 300 GeV electrons and positrons, E690 a 800 GeV/ c proton beam, HyperCP a mixed beam of π^+ , K^+ and protons ranging in momentum from 50 to 250 GeV/ c and SELEX a 600 GeV/ c mixed beam of π , K and Σ^- . HERA-B [28] and SPHINX [34] at HERA and IHEP (Protvino, Russia) also were fixed target experiments, both using proton beams – 900 GeV/ c at HERA and 70 GeV/ c at IHEP. COMPASS [24] is a fixed target experiment at CERN using a 160 GeV/ c μ^+ beam. The LASS spectrometer at SLAC collected data using a 11 GeV/ c K^+ beam and these data were recently re-analyzed [30]. WA89 is a fixed target at experiment

that used a 340 GeV/c Σ^- beam at CERN [36]. The PHENIX detector searched for the θ^+ in $Au - Au$ collisions [32] at RHIC.

4. Comparing the positive and negative results

Since the Ξ_5 and θ_c have only been observed by one experiment each, we discuss these states first and then discuss the θ^+ .

4.1. The Ξ_5 and θ_c

The Ξ_5 has only been observed by NA49 [17] and searched for, but not observed, by 9 experiments [16, 19, 20, 23, 24, 26, 27, 28, 36] as shown in Table 2. In the $\Xi^- \pi^-$ mode NA49 reports 38 signal (s) events over a background (b) of 43 events and thus claim a signal significance ($s.d.$) of 4.2σ assuming $s.d. = s/\sqrt{s+b}$. When they combine events from the $\Xi^- \pi^+$ mode as well then $s = 69$, $b = 75$ and $s.d. = 5.8\sigma$. NA49 observes a total of 1640 $\Xi^-(1320)$ in their sample. By contrast ALEPH, HERA-B, CDF, BaBar and WA89 have samples that exceed the NA49 sample of $\Xi(1320)$ by factors of 2, 10, 22, 157 and 412 respectively and all but NA49 fail to observe the Ξ_5 . Perhaps even more relevant are the numbers of $\Xi(1530)$ states observed. NA49 finds 150 $\Xi(1530)$'s [39] while ALEPH and ZEUS also see a comparable number but CDF sees 6 times more and BaBar and E690 see 100 times more. Not only are the statistics of the experiments that do not observe the Ξ_5 significantly higher, but the typical mass resolution of 1 to 2 MeV/ c^2 is much better than the resolution of NA49. It is hard to reconcile the existence of the Ξ_5 with this overwhelming negative evidence.

The θ_c has only been observed by H1 [18] and searched for, but not observed, by 6 experiments [19, 21, 22, 23, 27, 16] as shown in Table 2, H1 sees $s \approx 50$, $b \approx 50$ and claim $s.d. = 5\sigma$. The θ_c is observed in its decay to $D^{*+} \bar{p}$ and $D^{*-} p$. H1 has ≈ 3000 D^* 's in their sample and by contrast the number of D^* 's observed by FOCUS and CDF exceed the H1 sample by factors of 12 and 178 respectively. The failure of ZEUS to find the θ_c is particularly relevant because H1 and ZEUS are similar experiments operating at the same accelerator facility. It is hard to reconcile the existence of the θ_c with this overwhelming negative evidence.

4.2. Comparing positive θ^+ sightings with the null results

As shown in Table 1, the θ^+ has been observed in 13 reactions where two of the reports are from the LEPS group [4, 5] and another two from the CLAS group [6, 7]. As shown in Table 2, the θ^+ has been searched for by 16 separate experiments and all those came up with null results.

An interesting benchmark to compare the positive sightings with the null results is the number of observed $\Lambda(1520) \rightarrow pK^-$ decays. The number of claimed signal events s_θ and observed $\Lambda(1520)$ decays s_Λ for LEPS(1) is $s_\theta(s_\Lambda) = 19(25)$. For the other positive sightings, $s_\theta(s_\Lambda)$ for LEPS(2), CLAS(d), SAPHIR, HERMES and ZEUS are 56(162), 43(212), 55(530), 51(850) and 230(193) respectively. By contrast, the number of $\Lambda(1520)$ decays observed by ALEPH, BaBar, BELLE, CDF, E690, HERA-B and SPHINX (in thousands of events) are 2.8K, 100K, 15.5K, 3.3K, 5K and 23K. So, for example, the BaBar yield of $\Lambda(1520)$ decays exceeds that of LEPS(1) by a factor of 4000.

It seems difficult to reconcile the positive sightings with the null results since each of the two set of experiments spans a wide variety of production mechanisms. And in general the experiments yielding null results have higher statistics and superior resolution.

5. Examining the positive θ^+ sightings in more detail

Since the existence of a flavor-exotic baryon state would have such an important impact on our understanding of hadronic physics it is essential that the positive evidence be examined critically. In particular, we will discuss

- a) The statistical significance of the purported signals including a discussion of the background estimation;
- b) The effect of kinematical reflections giving rise to enhancements that could fluctuate to sharp peaks;
- c) Other possibilities of generating sharp peaks including *ghost tracks*, kinematic cuts and other mechanisms;
- d) Effects that could impair the isolation of exclusive reactions; and
- e) Problems of width estimates and consistency of masses among experiments.

Table 3. A tabulation of statistics for the observations of the θ^+ . See text for descriptions of the statistical significance as quoted in the three columns of ratios. The column labeled Published is the significance quoted in the publication.

Experiment	Signal s	Background b	Significance			
			Published	$\frac{s}{\sqrt{b}}$	$\frac{s}{\sqrt{s+b}}$	$\frac{s}{\sqrt{s+2b}}$
LEPS(1) [4]	19	17	4.6	4.6	3.2	2.6
LEPS(2) [5]	56	162		4.4	3.8	2.9
CLAS(d) [6]	43	54	5.2	5.9	4.4	3.5
CLAS(p) [7]	41	35	7.8	6.9	4.7	3.9
SAPHIR [8]	55	56	4.8	7.3	5.2	4.3
COSY [9]	57	95	4 – 6	5.9	4.7	3.7
JINR [10]	88	192	5.5	6.4	5.3	4.1
SVD [11]	35	93	5.6	3.6	3.1	2.4
DIANA [12]	29	44	4.4	4.4	3.4	2.7
ν BC [13]	18	9	6.7	6.0	3.5	3.0
NOMAD [14]	33	59	4.3	4.3	3.4	2.7
HERMES [15]	51	150	4.3 – 6.2	4.2	3.6	2.7
ZEUS [16]	230	1080	4.6	7.0	6.4	4.7

5.1. Statistical significance of positive sightings

Table 3 lists the number of signal events and background events for each of the positive sightings along with the published statistical significance of the θ^+ . The simple estimators rely on two numbers. The first is the number of background counts under the peak, b , while the second is the number of signal counts in the peak, s above background. From these two numbers, there are three commonly used significance estimators.

- (i) s/\sqrt{b}
- (ii) $s/\sqrt{s+b}$
- (iii) $s/\sqrt{s+2b}$

The first of these neglects the statistical uncertainty of the background and is normally an overestimate of the true significance. This is the most commonly quoted estimator for observed pentaquark signals. The second estimator assumes a smooth background with a well defined shape. Finally, the third method takes into account the uncertainty in a statistically independent background under the signal. This latter method should normally underestimate the true

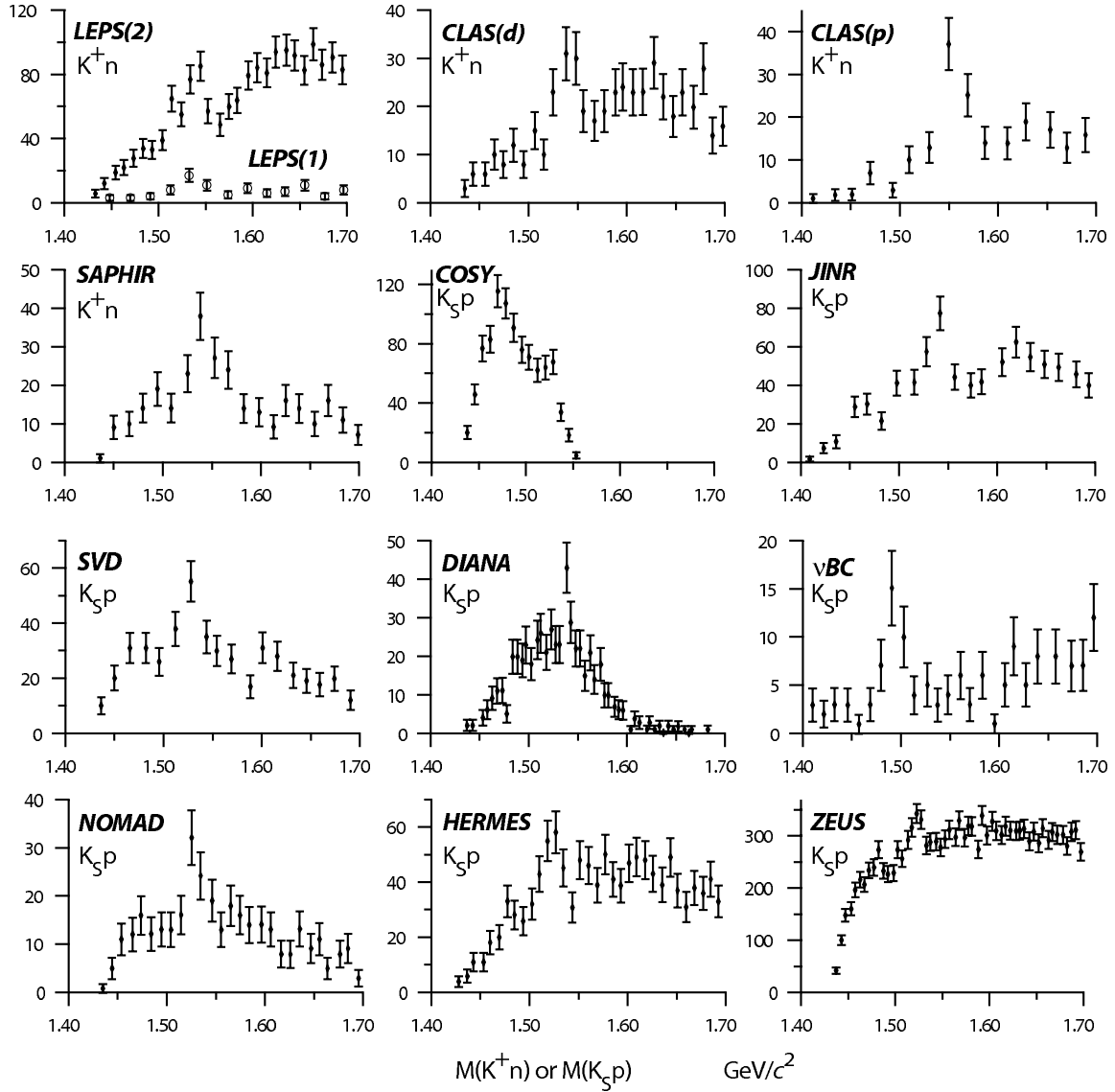


Figure 2. A comparison of the mass distributions for the K^+n or K_S^0p mass distributions for the experiments listed in Table 1. Only the mass region from 1.4 to 1.7 GeV/c^2 is shown. Error bars are based simply on statistical errors.

significance of an observed signal. All three estimators are computed for each sighting in Table 3. Since all of these experiments report on a signal with an unknown production mechanism over a background that is not understood, the best statistical measure is likely to be case (iii), $s/\sqrt{s+2b}$.

In Figure 2 we show the K^+n or K_S^0p mass distributions for the experiments listed in Table 1 absent any background curves. Only the mass region from 1.4 to 1.7 GeV/c^2 is shown. Error bars are based simply on statistical errors.

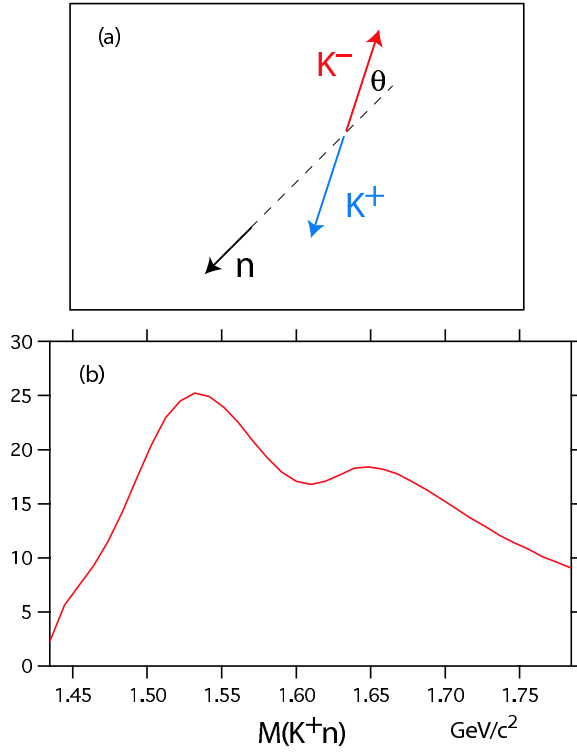


Figure 3. For the reaction $\gamma n \rightarrow K^+ K^- n$ the configuration of momentum vectors is shown in Figure (a) in the $K^+ K^-$ rest frame where the boost direction to this frame defines the axis. As discussed in [40] the decays of mesons, such as the ϕ , a_2 , f_2 and ρ_3 , with their characteristic decay structure and interference with each other, will influence the shape of the $K^+ n$ (and $K^- n$) mass distribution. The curve shown in Figure (b) is a possible description of the background for the observed $K^+ n$ spectrum reported in [6] and results from a simultaneous fit of the $K^+ n$, $K^- n$ and $K^+ K^-$ effective mass distributions with an assumption that the ϕ , a_2 , f_2 and ρ_3 are produced and then decay into $K^+ K^-$.

5.2. Kinematic reflections

It was pointed out in reference [40] that for lower energy photon experiments [4, 5, 6, 7, 8] the production of mesons, such as the ϕ , a_2 , f_2 and ρ_3 , with subsequent decays into $K^+ K^-$ could lead to structure in the $K^+ n$ mass distribution. This comes about because of the decay pattern of the decaying mesons given by $|Y_\ell^m(\theta, \phi)|^2$ and is illustrated in Figure 3. In part (a) of Figure 3 the momentum vectors in the rest frame of the decaying mesons is shown. The boost direction is along the line-of-flight of the meson and in this *helicity* frame that direction defines the z -axis. When the polar angle θ is small, the K^+ and n momenta are nearly collinear and the $K^+ n$ effective mass is small. For $\theta \approx \pi$ the effective mass is large. There is strong forward-backward peaking because of the $|Y_\ell^m(\theta, \phi)|^2$ and this reflects in the $K^+ n$ effective mass spectrum. But because of the constrained kinematics, owing to the low beam momenta, only the lower peak survives. The curve shown in Figure 3(b) is a possible description of the background for the observed $K^+ n$ spectrum reported in [6] and results from a simultaneous fit of the $K^+ n$, $K^- n$ and $K^+ K^-$ effective mass distributions with an assumption that the ϕ , a_2 , f_2 and ρ_3 are produced and then decay into $K^+ K^-$.

In 1969 Anderson *et al* [41] performed a search for the Z^* in $\pi^- p \rightarrow K^- Z^*$ at 6 and 8 GeV/ c by looking at the missing mass recoiling against the K^- (as is the case as well for the LEPS(1), LEPS(2) and CLAS(d) searches). They found a peak at around 1.6 GeV/ c^2 that they eventually ascribed to a kinematic reflection due to production of mesons decaying into $K \bar{K}$. This was supported by Monte Carlo studies and the observations that the peak position changed as the beam energy changed.

Although such a mechanism cannot produce a sharp peak in the $K^+ n$ mass distribution it will reduce the statistical significance of a purported signal in the low-mass region where this background peaks. And it could well lead to fluctuations into a sharp peak with low statistics as is illustrated in Figure 4.

Using as a parent distribution the distribution shown in Figure 3, twenty histograms were randomly generated with statistics equal to the $K^+ n$ distribution presented in [6] – also shown

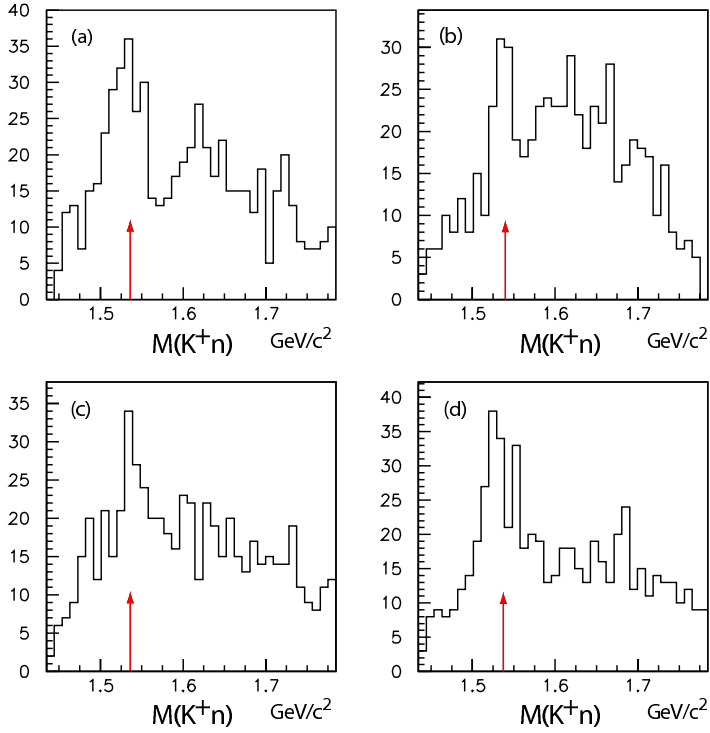


Figure 4. Using as a parent distribution, the distribution shown in Figure 3, 20 histograms were generated with statistics equal to the K^+n distribution presented in [6] – also shown in Figure (b). Of the 20 histograms, three were selected that had a sharp peak near the mass of θ^+ . These are shown in Figures (a), (c) and (d).

in part (b) of Figure 3. Of the 20 histograms generated, three were selected that had a sharp peak near the mass of θ^+ . These are shown in parts (a), (c) and (d) of Figure 4. The use of this mechanism to estimate the background for the CLAS(d) [6] data would result in a 20% probability of fluctuating into a sharp peak at the θ^+ mass.

5.3. Spurious peaks

Of the 13 θ^+ sightings list in Table 1, 8 are of the decay $\theta^+ \rightarrow K_S^0 p$ and of those all but two, COSY and DIANA, are inclusive measurements. It was pointed out by Zavertyaev [42] and Longo [43] that ghost tracks associated with the decay $\Lambda(1115) \rightarrow \pi^- p$ could lead to a spurious sharp spike at precisely $1.54 \text{ GeV}/c^2$ if $p_\Lambda > 2 \text{ GeV}/c$. The inclusive experiments should produce Λ 's copiously.

We illustrate this mechanism in Figure 4. In part (a) of that figure we show a schematic of a $\Lambda(1115) \rightarrow \pi^- p$ decay where the track reconstruction duplicated the proton track yielding an extra spurious positively charged track that has been assigned the mass of a pion. When combined with the π^- from the Λ^0 the effective mass clusters about $0.5 \text{ GeV}/c^2$ as in part (b) and when the ghost track is combined with the Λ^0 decay products the effective mass clusters around $1.5 \text{ GeV}/c^2$ as seen in part (c). In the shaded distributions the " $\pi^+ \pi^-$ " mass is required to be near the K_S^0 . The mean of the shaded portion of the distribution in part (c) is $1.54 \text{ GeV}/c^2$, the mass of the θ^+ . In this study the Λ^0 momentum in the LAB frame was uniform from 2 to $100 \text{ GeV}/c$.

The DIANA experiment shows a peak at the θ^+ mass of $1.54 \text{ GeV}/c^2$ (see Figure 2). But as pointed out by Zavertyaev [42], among the observed reactions should be charge exchange off a neutron, $K^+ n \rightarrow K_S^0 p$. This two-body reaction should yield a fixed $K_S^0 p$ effective mass if the K^+ beam momentum is fixed. Indeed the beam momentum spectrum is consistent with the position of the observed peak in the DIANA spectrum.

The CLAS(p) reaction $\gamma p \rightarrow K^+ K^- \pi^+ n$ [7] is an exclusive reaction uncomplicated by nuclear target effects (see the next subsection). After cuts are made to isolate this reaction the published

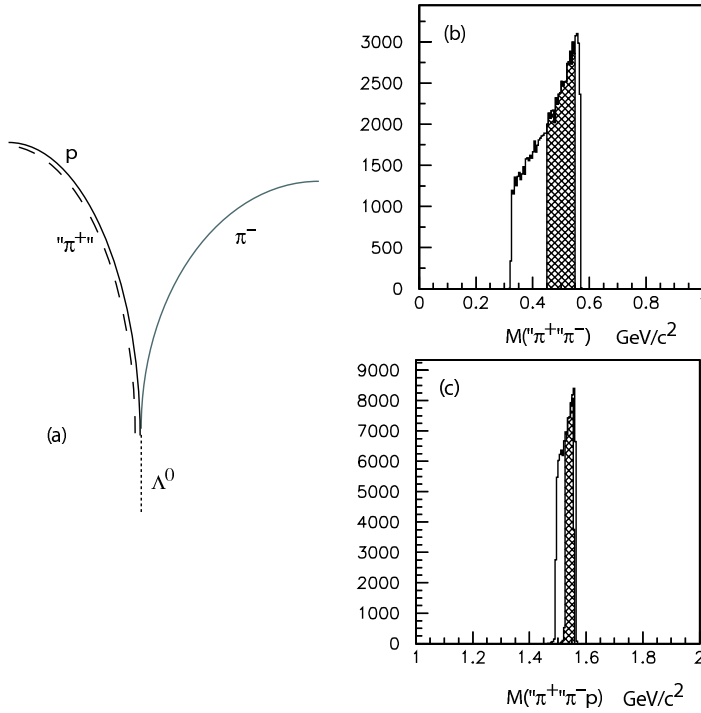


Figure 5. Figure (a) is a schematic of the decay $\Lambda^0(1115) \rightarrow \pi^- p$. The effect of spurious *ghost* tracks from the reconstruction software is considered. In this case a π^+ track is generated. When combined with the π^- from the Λ^0 the effective mass clusters about $0.5 \text{ GeV}/c^2$ as in Figure (b) and when the ghost track is combined with the Λ^0 decay products the effective mass clusters around $1.5 \text{ GeV}/c^2$ as seen in Figure (c). In the shaded distributions the " π^+ " " π^- " mass is required to be near the K_S^0 . The mean of the shaded portion of the distribution in Figure (c) is $1.54 \text{ GeV}/c^2$, the mass of the θ^+ . In this study the Λ^0 momentum in the LAB frame was uniform from 2 to 100 GeV/c .

K^+n mass spectrum shows no structure. But then kinematic cuts are made to remove processes that are potential backgrounds to θ^+ production such as:

- (i) $\gamma p \rightarrow X^+ n$ followed by $X^+ \rightarrow K^+ K^{*0} \rightarrow K^+ K^- \pi^+$
- (ii) $\gamma p \rightarrow X^0 N^{*+}/\Delta^+$ followed by $X^0 \rightarrow K^+ K^-$ and $N^{*+}/\Delta^+ \rightarrow n \pi^+$
- (iii) $\gamma p \rightarrow (X^0 \pi^+)_{\text{forward}} n$ followed by $X^0 \rightarrow K^+ K^-$

To remove these "backgrounds" the following cuts are made: $|t_{\gamma \rightarrow \pi}| \leq 0.28 \text{ (GeV}/c)^2$ and $\cos \theta_{K^+}^* \leq 0.6$ where $\theta_{K^+}^*$ is the angle of the K^+ in the overall center-of-mass. The result is a K^+n mass distribution sharply reduced in statistics but with a peak at the θ^+ . Furthermore it is claimed that the $K^- \theta^+$ effective mass shows a peak at $2.4 \text{ GeV}/c^2$ leading to the conclusion that an important mode for θ^+ production is $\gamma p \rightarrow \pi^+ N^*(2400)$ followed by $N^*(2400) \rightarrow K^- \theta^+$. The authors do not discuss the stability of observed peaks with respect to the kinematic cuts. We did Monte Carlo studies of reactions such as $\gamma p \rightarrow a_2^0 \Delta^+$ and found that the kinematic cuts can produce peaks observed in the CLAS(p) data depending on details of the spin-state of the a_2 .

Stoler also pointed out [44] that these data do show an anti-correlation of θ^+ signal with the K^* signal which is surprising since one might expect associated production of the θ^+ , *i.e.* $\gamma p \rightarrow K^{*0} \theta^+$ to be favored. However, this anti-correlation would be expected from a kinematical reflection.

5.4. Kinematic identification of reactions

The LEPS(1) and LEPS(2) reactions take place off a carbon nucleus leading to complications due to Fermi motion of the target nucleon. Because only the K^+ and K^- are measured, they then must assume that the unobserved neutron carries off the remaining missing momentum. In the case of CLAS(d), the θ^+ is observed in the effective mass of K^+n where the n is missing. However, to be able to reconstruct the reaction, the proton is required to have sufficient energy

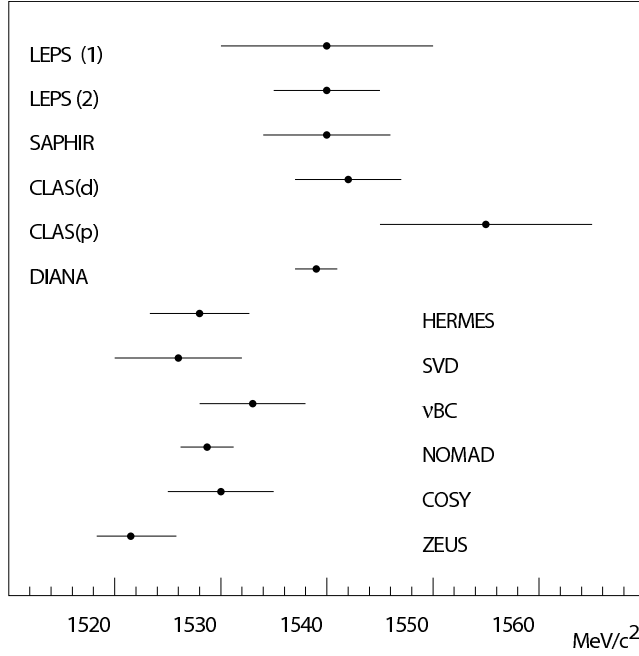


Figure 6. Reported masses, with error bars, of the θ^+ .

to escape the target. The proton is required to somehow be involved in the reaction, which leads to complications in understanding both the reaction itself and the backgrounds to the reaction.

The COSY experiment [9] depends on identification of the reaction $pp \rightarrow \Sigma^+ K_S^0 p$ but this experiment is highly unconstrained. This only information about this experiment is a collection of space-points from three pairs of hodoscope planes downstream of a "point" target. There is no momentum measurement, time measurement nor particle identification. The K_S^0 is identified through its decay into $\pi^+ \pi^-$ between the first and second hodoscope planes and the Σ is identified as a 'kink'. This experiment is seriously under-constrained and subject to backgrounds.

5.5. The reported masses and widths of the θ^+

Figure 6 shows a plot of the masses reported for the θ^+ . The quoted masses are inconsistent with each other although the reported widths are less than experimental resolution and these experiments accurately reproduce masses of established resonances.

Cahn and Trilling [45] analyzed the data from the DIANA experiment and conclude that the width of the θ^+ has a width of less than 1 MeV/c². Arndt *et al* [46] reanalyzed $K^+ N$ and conclude that the addition of the θ^+ with a width of about 5 MeV/c² is improbable but the data are consistent with a width of the θ^+ less than 1 MeV/c².

6. Summary and conclusions

The experimental evidence for the pentaquark states θ^+ , Ξ_5 and θ_c has been reviewed. The θ^+ has been observed in 13 reactions where two of the reports are from the LEPS group [4, 5] and another two from the CLAS group [6, 7]. The θ^+ has been searched for by 16 separate experiments and all those came up with null results. The positive sightings are complicated by nuclear target effects, mechanisms that can generate spurious peaks and problems with kinematic identification of final states. Furthermore, stringent cuts, the stability of which are not well understood, are required to isolate the peaks. On the other hand, experiments that have

searched for the θ^+ with null results have high statistics and superior resolution. The reported masses for the θ^+ are inconsistent with each other and the width is unusually small for a typical hadronic state. There have been attempts, *e.g.* Karliner and Lipkin [48], to understand all these results in terms of models that would suppress pentaquark production in some processes and not others. If it is real, the θ^+ is exotic not only in its flavor quantum numbers but also in its production and its decay.

The Ξ_5 has only been observed by NA49 [17] and searched for, but not observed, by 9 experiments [16, 19, 20, 23, 24, 26, 27, 28, 36]. It is hard to reconcile the existence of the Ξ_5 with this overwhelming negative evidence.

The θ_c has only been observed by H1 [18] and searched for, but not observed, by 6 experiments [16, 19, 21, 22, 23, 27]. It is hard to reconcile the existence of the θ_c with this overwhelming negative evidence.

Based on all this, the conclusion is that the experimental evidence for pentaquarks is very weak.

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8. References

- [1] Hey A and Kelly R, 1983 *Phys. Rep.* **96** 71
- [2] Trilling G, 2004 *A possible exotic baryon resonance*, a review from the Review of Particle Physics pdg.lbl.gov
- [3] Diakonov D, Petrov V and Polyakov M, 1997 *Z. Phys.* **359**, 305
- [4] Nakano T *et al*, 2003 *Phys. Rev. Lett.* **91**, 012002
- [5] Nakano T, 2004 Presented at QNP2004 www.qnp2004.org
- [6] Stepanyan S *et al* (CLAS Collaboration), 2003 *Phys. Rev. Lett.* **91**, 252001-1
- [7] Kubarovsky V *et al* (CLAS Collaboration), 2004 *Phys. Rev. Lett.* **92**, 032001-1
- [8] Barth J *et al* (SAPHIR Collaboration), 2003 *Phys. Lett.* **B572**, 127
- [9] Abdel-Bary M *et al* (COSY Collaboration), 2004 *Phys. Lett.* **B595**, 127
- [10] Aslanyan P, Emelyanenko V and Rikhkvitzkaya, 2004 hep-ex/0403044
- [11] Aleev A *et al*. (SVD Collaboration), 2004 hep-ex/0401024
- [12] Barmin V *et al*, 2003 *Phys. Atom. Nucl.* **66**, 1715
- [13] Asratyan A, Dolgolenko A and Kubantsev A, 2004 *Phys. Atom. Nucl.* **67**, 682
- [14] Camilleri L, 2004 Presented at the *Neutrinos 2004 Paris*, neutrino2004.in2p3.fr
- [15] Airapetian A *et al* (Hermes Collaboration), 2004 *Phys. Lett.* **B585**, 213
- [16] Chekanov S *et al* (ZEUS Collaboration), 2004 *Phys. Lett.* **B591**, 7
- [17] Alt C *et al* (NA49 Collaboration) 2004 *Phys. Rev. Lett.* **92**, 042003-1
- [18] Aktas, A *et al* (H1 Collaboration), 2004 *Phys. Lett.* **B588**, 17
- [19] Schael S *et al* (ALEPH Collaboration), 2004 *Phys. Lett.* **B599** 1 and CERN-PH-EP-2004-038
- [20] Aubert B *et al* (BaBar Collaboration), 2004 Presented at ICHEP2004 ic hep04.ihep.ac.cn and hep-ex/0408064
- [21] Mizuk R (BELLE Collaboration), 2004 Presented at ICHEP2004 ic hep04.ihep.ac.cn and hep-ex/0411005
- [22] Bai J *et al* (BES Collaboration), 2004 *Phys. Rev.* **D70** 012004 and hep-ex/0402012
- [23] Wang M-J *et al*. (CDF Collaboration), 2004 Presented at QNP2004 www.qnp2004.org; Gorelov I *et al* (The CDF Collaboration), 2004 Presented at DIS 2004 www.saske.sk/dis04 and hep-ex/0408025; Litvintsev D *et al* (The CDF Collaboration), 2004 Presented at BEACH2004 capp.iit.edu/beach04 and hep-ex/0410024
- [24] Brona G and Badelek B (COMPASS Collaboration), 2004 wwwcompass.cern.ch/compass/notes/2004-5
- [25] Lin C, 2004 Presented at ICHEP2004 ic hep04.ihep.ac.cn
- [26] Christian D *et al* (E690 Collaboration), 2004 Presented at QNP2004 www.qnp2004.org
- [27] Stenson, K (FOCUS Collaboration), 2004 Presented at the 2004 DPF Meeting hep-ex/0412021
- [28] Abt I *et al* (HERA-B Collaboration), 2004 *Phys. Rev. Lett.* **93** 212003 and hep-ex/0408048; Knoepfle, K *et al* (HERA-B Collaboration), 2004 *J. Phys.* **G30** S1363 and hep-ex/0403020
- [29] Longo M *et al* (HyperCP Collaboration), 2004 Presented at QNP2004 www.qnp2004.org and hep-ex/0410027
- [30] Napolitano J, Cummings J and Witkowski M, 2004 hep-ex/0412031

- [31] Armstrong S, 2004 Presented at BEACH2004 capp.iit.edu/beach04 and [hep-ex/0410080](#)
- [32] Pinkenburg C (PHENIX Collaboration), 2004 *J.Phys.* **G30** S1201 and [nucl-ex/0404001](#)
- [33] Engelfried J (SELEX Collaboration), 2004 Presented at Quark Confinement 2004 www.eurocongress.it/Quark
- [34] Antipov Yu *et al.* (SPHINX Collaboration), 2004 *Eur. Phys. J.* **A21** 455 and [hep-ex/0407026](#)
- [35] Salur S (STAR Collaboration), 2004 [hep-ex/0403009](#) and [nucl-ex/0410039](#)
- [36] Adamovich M *et al.* (WA89 Collaboration), 2004 [hep-ex/0405042](#)
- [37] (ZEUS Collaboration), 2004 Presented at ICHEP2004 ichep04.ihep.ac.cn
- [38] Chekanov S *et al* (ZEUS Collaboration), 2004 *Eur.Phys.J.* **C38** 29 and [hep-ex/0409033](#)
- [39] Fischer H and Wenig S, 2004 [hep-ex/0401014](#)
- [40] Dzierba A, Krop D, Swat M, Teige S and Szczepaniak A, 2004 *Phys. Rev.* **D69** 051901-1
- [41] Anderson E *et al*, 1969 *Phys. Lett.* **B29**, 136
- [42] Zavertyaev M, 2003 [hep-ph/0311250](#)
- [43] Longo M, 2004 Presentation of HyperCP at QNP2004 www.qnp2004.org
- [44] Stoler P, 2004 Presentation of CLAS results at QNP2004 www.qnp2004.org
- [45] Cahn R and Trilling G, 2004 *Phys. Rev.* **D69**, 011501-1
- [46] Arndt R, Strakovsky I and Workman R, 2003 *Phys. Rev.* **C68** 042201
- [47] Haidenbauer J and Krein G, 2003 *Phys. Rev.* **D68** 052201
- [48] Karliner M and Lipkin H, 2003 *Phys. Lett.* **B575**, 249